Characteristic Ellipsoid Approach to Monitor Power Systems Dynamic Behavior Using Phasor Measurements

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Introduction

- A new Characteristic Ellipsoid (CELL) method developed by PNNL
- Use sub-second synchrophasor measurements to monitor the dynamic behavior of power systems
- Preliminary study (FY07) was supported by PNNL's Laboratory Directed Research and Development (LDRD)
- Continuous study (FY08) was supported by the U.S. Department of Energy's Office of Electricity Delivery and Energy Reliability (Phil Overholt) through the Consortium for Electric Reliability Technology Solutions (CERTS) (Jeff Dagle, Joe Eto)
- Develop a real-time tool at prototype level for
  - Providing wide-area situational awareness for grid operators
  - Identifying system disturbances
  - Detecting system stresses, their timing and locations
  - Ultimately: actionable decision support to operators and remedial action schemes

Project Team & Cooperation

- Project Team
  - Dr. Yuri Makarov (PI, Chief Scientist, PNNL)
  - Dr. Jian Ma (Project Leader, Engineer, PNNL)
  - Dr. Ning Zhou (Senior Engineer, PNNL)
  - Mr. Jeff Dagle, P.E. (Chief Engineer, PNNL)
  - Dr. Pavel Etingov (Senior Researcher, Energy Systems Institue, Russia)
  - Dr. Enrico De Tuglie (Assoc/Prof., Politecnico di Bari, Italy)
  - Mr. Carl H. Miller (Engineer, PNNL)
  - Dr. Tony B. Nguyen (Senior Engineer, PNNL)
- Cooperation/Initial Contacts
  - Midwest ISO – Initial Disscusion (Dr. Terry Bilke)
  - North Dakota State University – Cooperation Agreement (A./Prof. Lingling Fan)
  - CAISO – In-kind Collaboration (Dr. Soumen Ghosh, Dr. Matthew Varghese, Clyde Loutan, P.E., Tammy Elliott, et al.)
  - NERC – Initial Disscusion (Dr. Bob Cummings)
  - Southern Company – Presentation, Initial Discussion (Dr. Clifton Black, et al.)
  - ISO New England – Presentation (Dr. Eugene Litvinov, et al.)
  - Politecnico di Bari (Assoc/Prof. Enrico De Tuglie)

The CELL Methodology

- The CELL contains a certain part of the system trajectory.
- An optimization procedure to minimize the volume of the multidimensional CELL with the constraints keeping all points of the system trajectory inside the CELL.
- The key characteristics of a CELL: volume, eccentricity, characteristic sizes (semi-axes), orientation of semi-axes, and parameter trends in time, including the generalized damping (the derivative of the CELL's volume).

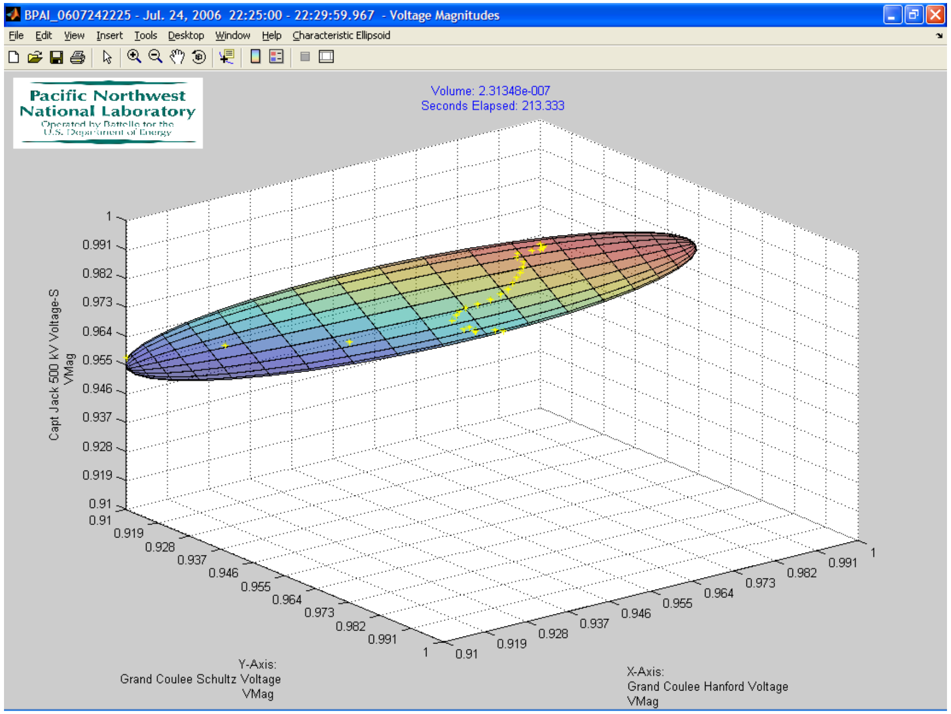


Fig. 1. A 3-dimensional characteristic ellipsoid

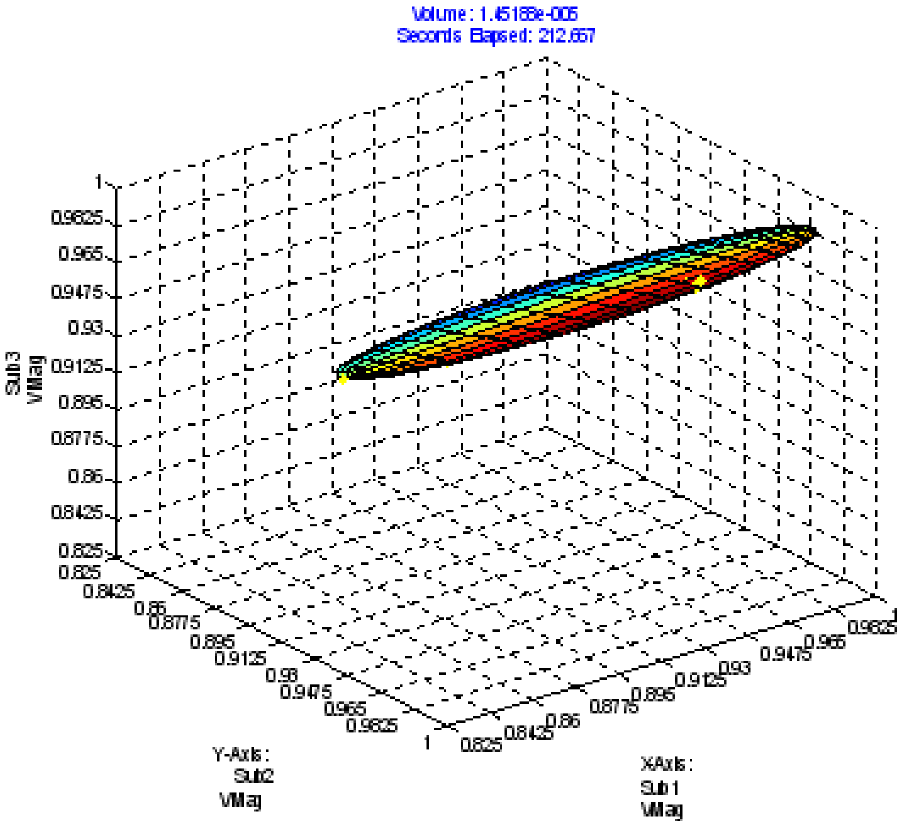
- These characteristics will be then translated into the physically meaningful power system events and characteristics: disturbances, damping, coherency of oscillations, and others.

Interpretation Rules (Example)

- Interpretation rules link the mathematical indexes of CELL with actionable information.
- CELL's volume $V(E_{A,c})$ is a measure of system stress reflecting the spatial magnitude of the system trajectory.
- Sudden change of volume indicate the system disturbances.
- The derivative of volume with regard to time measures generalized damping of the system motion
- The eccentricity of CELL indicates the disturbance of the systems, and how wide the disturbance is.
- The projections of the dominate radius reflect locations of disturbances in a power system.
- The eigenvector $u_{\max} = u_i$ corresponding to the smallest λ_i indicates the dominating direction of the system motion.
- The angles between eigenvector and coordinates help to identify phasors (and system locations) involved in the system's dominating motion.
- The orientation of eigenvector helps to understand whether the phasors move in phase or out of phase.

WECC System Disturbance Analysis

- Apply the CELL method to a real disturbance in WECC system.
- Voltage magnitude and frequency at the selected locations are shown.
- Derivative of the CELL volume constructed from normalized voltage magnitude.



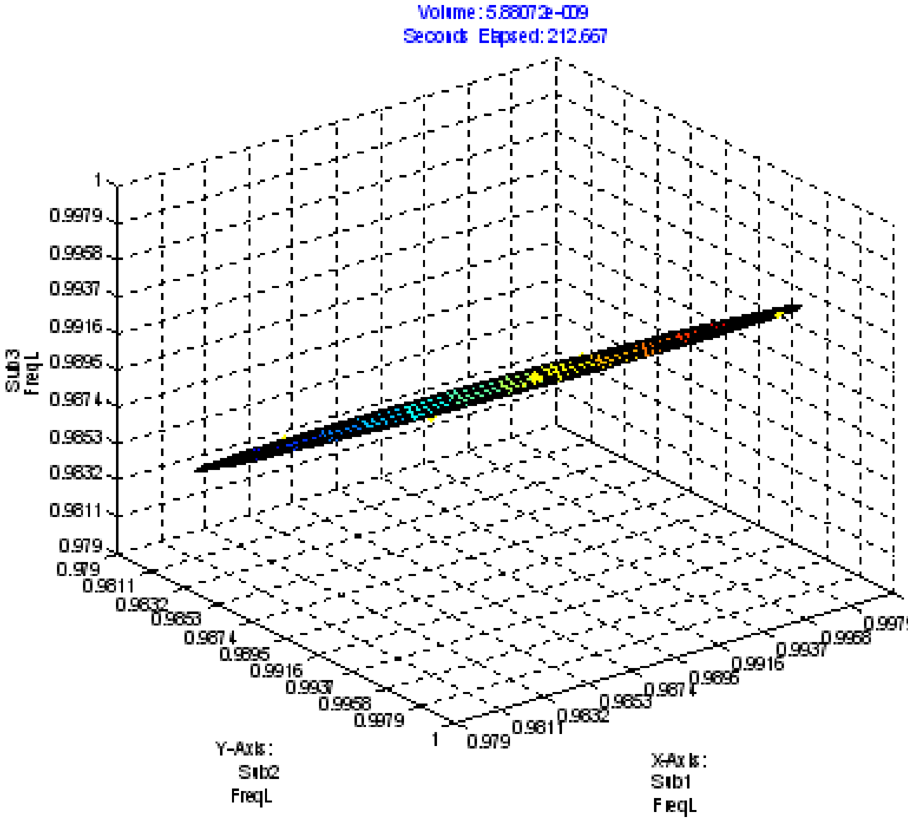


Fig. 2. Characteristic ellipsoids before and after the disturbance.

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WECC System Disturbance Analysis

- Western Interconnection system disturbance on July 24, 2006. During this disturbance, a 500-kV transmission line in the Northwest region faulted and tripped to lock out at 15:28:32.4 PDT. The protective scheme dropped 1661 MW of the generation, inserted 1400-MW breaking resistor at a substation for 0.5 seconds, and inserted 500-kV shunt capacitor at another substation.
- Voltage magnitude and frequency at the selected locations are shown.
- Derivative of the CELL volume constructed from normalized voltage magnitude.
- CELL detected the disturbance successfully.

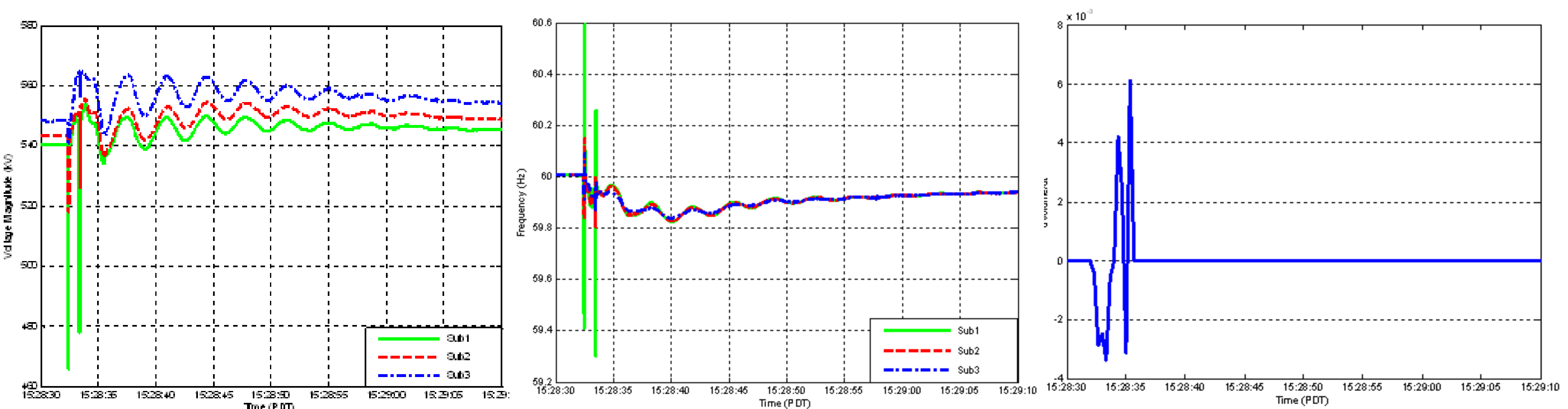

Fig. 3. Volume change of characteristic ellipsoids during the disturbance.

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Voltage Collapse Analysis: IEEE 68-bus Test System

- Use CELL to detect the system stress.
- The system is approaching its stability boundary.
- Volume and eccentricity of the CELL based on voltage magnitude.
- CELL reflects system stress when the voltage itself cannot provide such information.

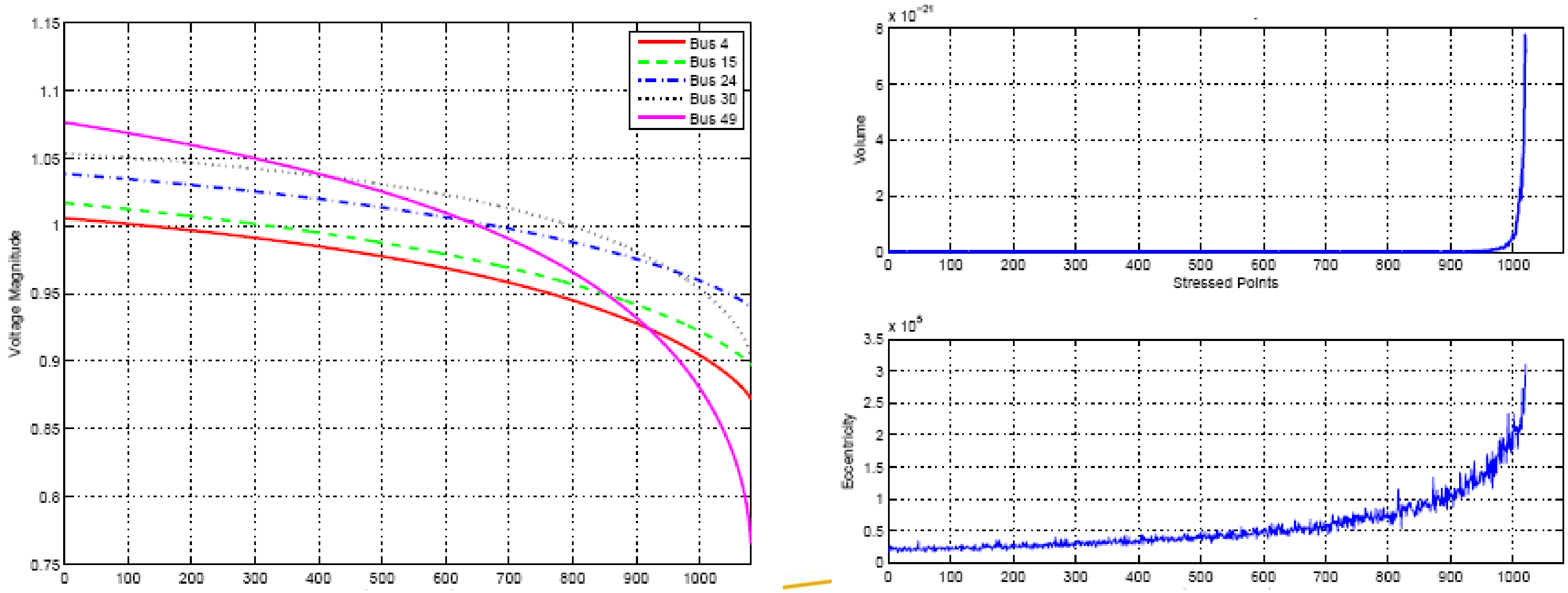

Fig. 4. Voltage magnitude at buses 4, 15, 24, 30, and 49, and the volume and eccentricity of characteristic ellipsoids.

Decision Trees

- IEEE 68-bus test system divided into six zones.
- To identifying and locating power system disturbances.
- Three-phase fault at different locations with different durations was used as the disturbances.
- Projections of the semi-axes of the ellipsoid at the global coordinate system were used.
- Link the ellipsoid mathematical index to the actionable actions of power systems.
- Provide a way to interpret CELL’s mathematical characteristics.

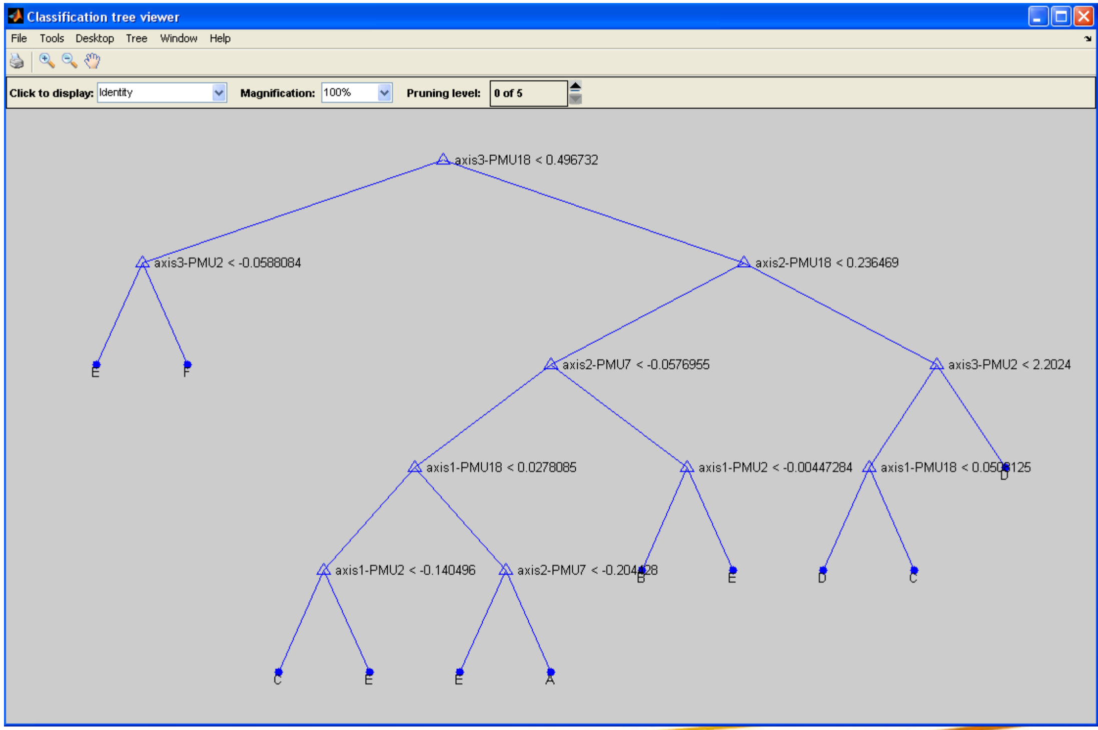

Fig. 5. An example of decision tree.

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Publications

1. Y. V. Makarov, J. Ma, E. De Tuglie, and N. Zhou, “Characteristic ellipsoid method and its applications,” *IEEE Transactions on Power Systems*, 2008 (to be submitted).
2. Y. V. Makarov, J. Ma, N. Zhou, J. E. Dagle, P. V. Etingov, and E. De Tuglie, “Characteristic Ellipsoid Method to Monitor Power Systems Dynamic”, PNNL Project Report, Prepared for U.S. Department of Energy (DOE), Sep. 2008.
3. J. Ma, Y. V. Makarov, C. H. Miller, and T. B. Nguyen, “Use multi-dimensional ellipsoid to monitor dynamic behavior of power systems based on PMU measurement,” in *Proceedings of IEEE PES General Meeting*, Pittsburgh, PA, July 20-24, 2008.
4. Y. V. Makarov, J. Ma, N. Zhou, C. H. Miller, T. B. Nguen, and E. De Tuglie, “A new CELL method to monitor power system dynamics,” *The 6th Mediterranean Conference and Exhibition on Power Generation, Transmission and Distribution, Thessaloniki*, Greece, Paper #65, Nov. 2–5, 2008 (Accepted).
5. Y. V. Makarov, C. H. Miller, T. B. Nguyen, and J. Ma, “Monitoring of power system dynamic behavior using characteristic ellipsoid method,” in *Proceedings of The 41th Hawaii International Conference on System Sciences*, Hawaii, Jan. 7-10, 2008.
6. Y. V. Makarov, C. H. Miller, T. B. Nguen, and J. Ma, “Characteristic ellipsoid method for monitoring power system dynamic behavior using phasor measurements," in *Proceedings of IREP: An International Symposium on Bulk Power Systems Dynamics and Control –VII Revitalizing Operational Reliability*, Charleston, South Carolina, USA, Aug. 19-24, 2007.
7. J. Ma, “Chapter 7, Using multi-dimensional ellipsoid to monitor dynamic behavior of power systems,” in *Advanced Techniques for Power System Stability Analysis*, *Ph.D Dissertation*, The University of Queensland, Australia, Mar. 2008.

Future Work

- Link the CELL characteristics to the real system behavior
- Framework of a real-time application system
- Decision trees and interpretation rules
- Develop a software tool
  - real-time situation
  - Graphic User Interface (GUI)
  - multi-dimensional characteristic visualization – attainability tubes
  - on-line and off-line building decision trees
  - multiple approaches for message presentation (text, voice and graphs etc.)
  - study mode and real-time mode
- Test the software tool in PNNL's Electricity Infrastructure Operations Center (EIOC).

Thanks!